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The rotational evolution of single and binary solar twins using HARPS spectra

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Abstract. Recent discoveries of extra-solar planets around cool stars show that they have unusual properties which are unseen in the Solar System. In light of this fact, many questions have been posed regarding if the Sun is a typical star for its type and age. In particular, assessing if the Sun is a common rotator has important implications for gyrochronology and our understanding of the rotational evolution of Sun-like stars. In The Solar Twin Planet Search program we observed more than 80 Sun-like stars using the HARPS spectrograph with the objective of procuring extra-solar planets. The high-quality spectra obtained in this program allowed us to perform an unprecedent study on the rotational evolution of stars strictly similar to the Sun, and thus assess if it is a regular rotator. Our results show that the Sun indeed rotates tipically for its age, but the solar twins in general seem to plateau in their rotational velocity evolution after the solar age; the rotational periods, on the other hand, should continue to evolve through the main sequence. In addition, we found that the solar binaries do not follow a distinct evolutionary path in their rotation, and we discuss the outliers in our sample.

Resumo. Descobertas recentes de planetas extrassolares em estrelas do tipo solar mostram que eles têm propriedades incomuns quando comparadas com o Sistema Solar. Em vista desse fato, muitas questões foram feitas se o Sol é uma estrela típica para o seu tipo e idade. Em particular, avaliar se o Sol tem uma rotação comum tem implicações importantes para girocronologia e nosso entendimento sobre a evolução rotacional de estrelas similares. No programa *Solar Twin Planet Search* nós observamos mais de 80 gêmeas solares com o espectrógrafo HARPS com o objetivo de procurar planetas extrassolares. Os espectros de alta qualidade obtidos nesse programa permitiram um estudo sem precedentes sobre a evolução rotacional de estrelas estritamente similares ao Sol, e portanto verificar se ele é um rotador regular. Nossos resultados mostram que o Sol realmente rota tipicamente para sua idade, mas as gêmeas solares em geral parecem estagnar em sua evolução rotacional depois da idade solar; os períodos de rotação, por outro lado, devem continuar evoluindo ao longo da sequência principal. Além disso, também verificamos que as gêmeas solares binárias não seguem um caminho evolutivo distinto em sua rotação, e discutimos os principais casos de desvios da norma.

Keywords. Stars: solar-type – Stars: fundamental parameters – Stars: evolution – Stars: rotation – *(Stars:)* binaries: spectroscopic – Sun: evolution

1. Introduction

The wealth of high-quality photometric and spectroscopic data produced by the search for extra-solar planets fueled a growing interest in questions regarding the magnetic and rotational evolution of Sun-like stars (e.g., Gallet & Bouvier 2013; do Nascimento et al. 2014; Amard et al. 2016). The Sun is the only star for which we have wide access to accurate and precise direct measurements of its physical properties, thus we rely heavily on the knowledge of our star to infer about other stars and their planetary systems. Such indirect inferences are made, however, based on the premise that the Sun is a typical star; it is thus crucial that we assess this assumption by comparing the Sun with other stars, preferably those that display similar physical properties.

Past studies in the rotation of the Sun rendered conflicting results, often suggesting that it either rotates too slowly (Smith 1979; Leão et al. 2015) or regularly for its age (e.g., Soderblom 1983; Barnes 2003). However, such comparisons were made against stars with relaxed degrees of similarity to the Sun, thus precluding us of drawing reliable conclusions on the conformity of the solar rotation.

Simple models of stellar wind and rotational evolution for Sun-like stars predict that, during the main sequence, their rotational velocities and chromospheric activity correlate with stellar ages according to a power-law ($v_{\rm rot} \propto t^{-\beta}$, Kawaler 1988). This power-law index β is related to the magnetic field configuration of the star, which in turn controls how much angular momentum is lost through stellar wind (Charbonneau 1992; Barnes 2003; Gallet & Bouvier 2013). The first strong observational evidence for this evolution was obtained in the seminal work of Skumanich (1972), in which they found that $\beta = 1/2$. This strong connection between rotational rate and stellar age gave life to gyrochronology, which is calibrated to match the solar values (Barnes 2007; Mamajek & Hillenbrand 2008). This relation allows us to reliably derive stellar ages if we know the rotational rate of a star and if we assume that the Sun is a typical rotator. Moreover, we expect that Sun-like stars orbited by close-in stellar or sub-stellar companions have enhanced rotational velocity and chromospheric activity due to interaction with their companions (e.g., Ferraz-Mello et al. 2015).

In the Solar Twin Planet Search program we used the HARPS spectrograph (High-Accuracy Radial velocity Planet Searcher, Mayor et al. 2003) to observe more than 80 solar twins aiming to procure extra-solar planets orbiting bright ($V < 10$) Sun-like stars (Ramírez et al. 2014; Bedell et al. 2015; Tucci Maia et al. 2016; dos Santos et al. 2016, 2017; Meléndez et al. 2017). When corrected for barycentric radial-velocities, the spectra of each star can be combined to produce extreme high signal-to-noise ratio (median SNR ~ 1000 at 600 nm), which in turn allowed us to precisely measure the physical parameters of the solar twins using differential analysis (Bedell et al. 2014). This sample contains 18 spectroscopic binaries, of which three display high rotational velocities for their ages.

We used this large sample of solar twins with high-precision physical parameters to reliably infer if the Sun is a typical rotator for its age, as well as to study the rotational evolution of Sun-like stars. In addition, we employed the radial velocities (RVs) data from HARPS to obtain the orbital parameters of the solar twin binaries and measure the orbital parameters of these systems. In the following sections we discuss our main results and their implications for stellar evolution of Sun-like stars and binary systems.

2. Data analysis of MIKE and HARPS spectra

Initially, we observed 88 solar twins with the MIKE spectrograph (Magellan Inamori Kyocera Echelle, Bernstein et al. 2003) and from these spectra derived the stellar parameters – effective temperature $T_{\rm eff}$, surface gravity $\log g$, metallicity [Fe/H] and stellar ages t – following the procedure described in Ramírez et al. (2014). Later we noticed that the spectral resolution of MIKE is not stable enough to measure rotational velocities $v \sin i$, leading us to use the HARPS spectra to perform this measurement. The other stellar parameters derived from the HARPS spectra are going to be published in a forthcoming paper (Spina et al. 2017).

Since rotational velocities of solar twins are usually lower than 4 km s^{-1}, it is necessary to use spectra with high resolving power ($R > 10^5$) and high signal to noise (SNR > 500) to reliably measure rotational velocities (see figures 1 and 2 in dos Santos et al. 2016). The HARPS spectra are initially processed with the Data Reduction Software (DRS) available for the instrument's users; this software also computes barycentric radial velocities by cross-correlating the spectra with a binary mask of a solar-type star. Further description of the data processing and details on how rotational velocities are measured can be found in dos Santos et al. (2016). Essentially, we combined the HARPS spectra after the radial velocity Doppler correction and the rotational velocities were measured by comparing five observed spectral lines with synthetic lines computed with MOOG (Sneden 1973) and atmosphere models by Castelli & Kurucz (2004). These measurements took into account the contribution of macroturbulence velocity for each star, which is computed following an empirical relation (see equation 1 in dos Santos et al. 2016).

The stellar ages were computed from the MIKE spectra by fitting the stellar parameters with Yonsei-Yale isochronal tracks (Yi et al. 2001), following the procedures of Ramírez et al. (2013, 2014). There are many concerns with the use of isochrones to estimate stellar ages. As shown by Brown (2014), these Bayesian age estimates may be biased towards larger values, although this problem can be minimized by using specific techniques (see Ramírez et al. 2013, and references therein). It is also important to consider that stellar evolution models used to generate the isochrone tracks have limitations, which are mainly related to uncertainties in the input physics and the lack of non-standard physics; for a detailed analysis of the main differences between different stellar evolution models and their limitations, we refer to Stancliffe et al. (2016). Nevertheless, most of these concerns should not be important for stars extremely similar to the Sun, especially for stellar ages near solar age (4.56 Gyr, Bahcall et al. 1995), as the isochrones we use were calibrated to reproduce the solar age and mass (Meléndez et al. 2012).

The orbital parameters of the spectroscopic binaries were estimated following the formalism of Murray & Correia (2010). The best fit parameters are obtained using an implementation of the Nelder-Mead algorithm to minimize the residuals of the fit to a Keplerian reflex motion; the uncertainties of the fit were estimated with `emcee`, an implementation of the Affine Invariant Markov Chain Monte Carlo Ensemble sample (Foreman-Mackey et al. 2013). In addition, we also included radial velocities obtained in other instruments in order to extend the time coverage of the data. More details in the implementation of this method can be found in dos Santos et al. (2017).

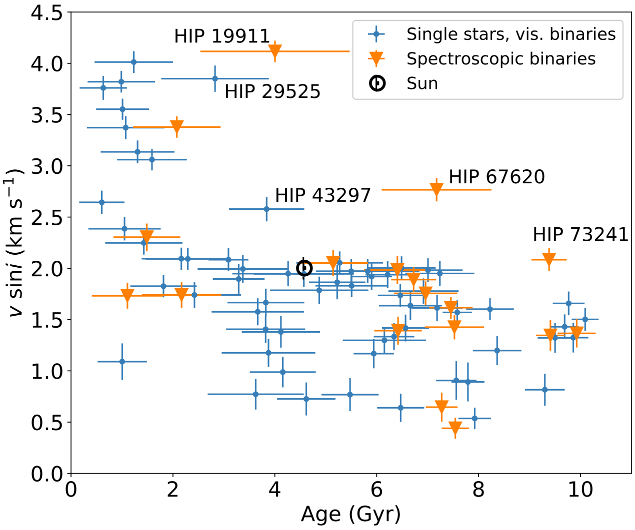

Figure 1. The rotational velocities and stellar ages of all solar twins that were observed with HARPS.

3. The relation between rotational velocities and stellar ages

Rotational velocities measured with stellar spectra are multiplied by $\sin i$, where i is the inclination angle of the rotational axis of the star and the reference plane; this angle is unknown for most stars in our sample, and this limitation introduces a significant spread in the $v \sin i$ versus age relation (see Fig. 1). An isotropic distribution of inclination angles i results in a distribution of $\sin i$ that is biased towards 1; in fact, it is expected that all stars above the 70th percentile of $v \sin i$ in a given interval of ages have $\sin i$ above 0.9. This allows us to select the stars that have the highest chances of having $\sin i \approx 1$ inside age bins with widths of 2 Gyr (see Section 5 in dos Santos et al. 2016). In addition, we remove spectroscopic binaries from the sample, since we start from the premise that these may display distinct evolutionary paths due to interactions with their close-in companions.

We then proceeded to fit an empirical relation between rotational velocities and ages similar to the one inferred by Skumanich (1972). We decided to utilize the functional form of a power-law added of a constant[1]: $v = v_{\rm f} + m\, t^{-b}$, where v is the rotational velocity (km s^{-1}), t is the age (Gyr), and $v_{\rm f}$ (asymptotic velocity, km s^{-1}), m and b are free parameters. The best-fit values for the free parameters were obtained by fitting the data using the the method of orthogonal distance regression (ODR, Boggs & Rogers 1990), which takes into account the uncertainties in both $v \sin i$ and ages.

We found that the best-fit parameters are $v_{\rm f} = 1.224 \pm 0.447$, $m = 1.932 \pm 0.431$, and $b = 0.622 \pm 0.354$ (see Fig. 2). This result is in contrast with the previous empirical studies on the rotational

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[1] This same funcional form is also used by Pace & Pasquini (2004) and Guinan & Engle (2009) in their chromospheric activity and $v \sin i$ vs. age relations.

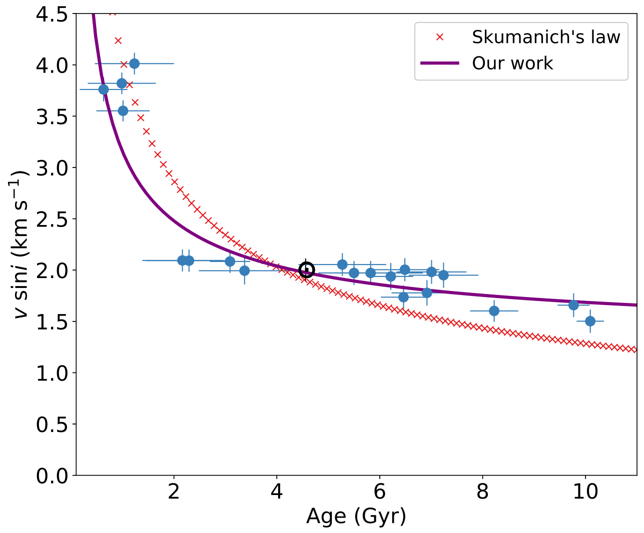

FIGURE 2. The rotational braking law that we obtained for the *selected sample* of solar twins. The light gray region is composed of 300 curves that are created with parameters drawn from a multivariate Gaussian distribution defined by the mean values of the fit parameters and their covariance matrix.

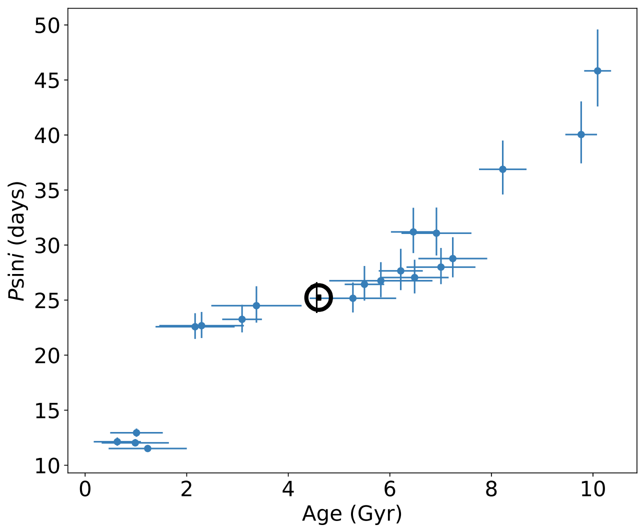

FIGURE 3. Expected evolution of rotational periods for the *selected sample* of solar twins, taking into account the theoretical evolution of radii from do Nascimento et al. (2014).

evolution of solar-type stars (Barnes 2001, 2003; Lanzafame & Spada 2015), which either found or assumed that the Skumanich law describes well the rotational braking of Sun-like stars. This conflict can be explained by the fact that using solar-type stars, which are not as similar to the Sun as solar twins, may introduce larger uncertainties in the $v \sin i$ and age relation; other line-broadening terms, such as macroturbulence velocities, may also contribute as a confounding factor.

Our results reinforce the idea that the Sun is indeed a normal star regarding its rotational velocity when compared to solar twins; this, in turn, validates the use of the Sun to calibrate gyrochronology relations. The solar twins, on the other hand, do not seem to follow the Skumanich law: their rotational velocities decay more steeply during the early ages, and plateau after the solar age. This result imposes a challenge for gyrochronology, since stars effectively older than the Sun have rotational velocities similar to solar, thus increasing the uncertainties of gyro ages. The rotational braking law we obtained agrees strongly with the theoretical model proposed by do Nascimento et al. (2014), and qualitatively with the empirical power-law index derived by Pace & Pasquini (2004, see Fig. 2).

A similar behavior of rotational stagnation after the solar age was also observed by van Saders et al. (2016) using rotational periods of *Kepler* stars and open clusters. However, due to the evolution of stellar radii during the end of the main sequence (do Nascimento et al. 2014), we expect that the rotational periods of Sun-like stars should become larger after 8 Gyr (see Fig. 3). Thus, although the rotational velocities saturate after the solar age, the rotational periods seem to increase, likely validating gyrochronology.

Among the non-spectroscopic binaries in our sample (blue symbols in Fig. 1), we noticed that HIP 29525 and HIP 43297 displayed rotational velocities significantly higher than the expected for their ages. A careful analysis of their stellar parameters using the HARPS spectra revealed that their ages were overestimated (Spina et al. 2017), which means that these are young stars (0.8 and 1.8 Gyr, respectively, for HIP 29525 and HIP 43297) with consistent rotational rates for their ages. The other fast-rotating stars in our sample are spectroscopic binaries and are discussed in Section 4.

4. Spectroscopic binaries

For the purposes of this study, spectroscopic binaries are those that show a significant modulation in their HARPS radial velocities that can be traced to the presence of a close-in companion or those with companions detected directly in separations smaller than 1 arcsec, which is the angular aperture of the HARPS spectrograph. We observed 18 spectroscopic binaries in our sample, and at least three of them display rotational velocities and chromospheric activity significantly higher than the expected for their ages: HIP 19911, HIP 67620, and HIP 103983 if we consider its updated age estimate (Spina et al. 2017; dos Santos et al. 2016; Freitas et al. 2017; Ramírez et al. 2014). In addition, the radial velocities fit for these three binaries display residuals larger than the expected for the high-quality data they have.

The orbital parameters we measured for the spectroscopic binaries with complete or near-complete phase coverage are shown in Table 1, including the fast-rotating binaries. With the exception of HIP 30037, we found that these systems display moderate orbital periods of more than one year and the minimum masses of their companions indicate that these are, in general, red or white dwarfs.

For HIP 19911 and HIP 67620, the direct detection of bright companions around them (Riddle et al. 2015; Tokovinin 2014; Hartkopf et al. 2012) suggest that their companions are red dwarfs, thus weakening the hypothesis of blue straggler phenomena to explain their anomalies. Further analysis of HIRES spectra of HIP 19911 reveals that this is a double-lined binary (see Fig. 4), which was not visible in the HARPS spectra because of unfavorable observation windows. A similar case is observed for HIP 67620, in which Fuhrmann et al. (2017) found that this is also a double-lined binary, displaying a weak Doppler separation of -7 km s^{-1}. For HIP 103983, a careful analysis of the HARPS spectra revealed that this is also a double-lined binary (see Fig. 5), but with a small Doppler separation that is only discernible when the system is near the periapse.

Table 1. Orbital parameters of the binaries with complete or near-complete orbital phases in their RV data. Results for HIP 83276 come from Duquennoy & Mayor (1991).

HIP	HD	T (days)	e	$m \sin i$ ($M_\odot$)	a (AU)
6407	8291	1852.3 $^{+3.3}_{-3.1}$	0.682 $^{+0.009}_{-0.010}$	0.119 ±0.002	3.070 ±0.005
14501	19467	–	–	> 0.043	–
18844	25874	–	–	> 0.075	–
19911	26990	2074.15 ±0.09	0.8188 ±0.0003	0.313 ±0.002	6.16 ±0.02
30037	45021	31.61112 ±0.00006	0.30205 ±0.00008	0.0610 ±0.0002	0.1971 ±0.0003
54102	96116	> 5110	–	0.012	–
54582	97037	> 37000	–	0.03	–
62039	110537	–	–	> 0.018	–
64150	114174	–	–	0.258	–
65708	117126	207.273 ±0.004	0.311 ±0.002	0.170 ±0.001	0.851 ±0.001
67620	120690	3803.3 ±0.4	0.3428 ±0.0002	0.578 ±0.002	5.50 ±0.01
72043	129814	> 38000	–	> 0.40	–
73241	131923	> 7670	–	> 0.49	> 0.72
79578	145825	6681.8 ±1.5	0.3322 ±0.0003	0.1014 ±0.0002	7.216 ±0.007
81746	150248	3246.5 ±0.7	0.6644 ±0.0005	0.1079 ±0.0002	4.387 ±0.003
83276	153631	386.72	0.185	0.24	–
87769	163441	> 30000	–	> 0.30	–
103983	200565	10278 $^{+274}_{-247}$	0.50 ±0.01	0.210 ±0.005	9.8 ±0.2

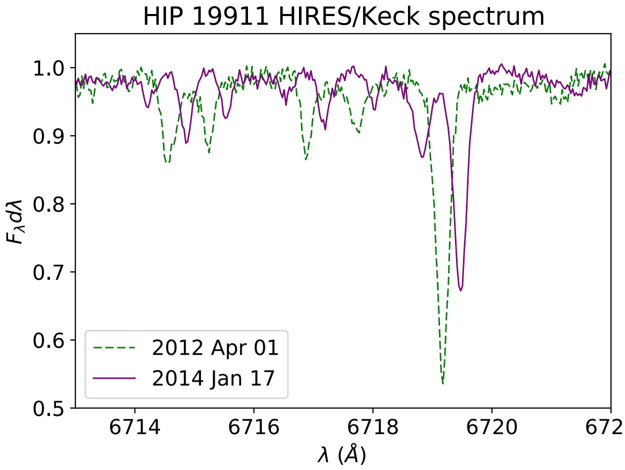

Figure 4. HIRES spectra for the double-lined solar twin binary HIP 19911 taken at two different orbital phases: lowest Doppler separation corresponds to the green spectrum, and the largest separation is represented by the purple spectrum.

These results indicate that solar twin binaries with low-mass companions at moderate or large orbital periods (> 30 days), either eccentric or not, do not seem to follow a distinct rotational evolutionary path than single solar twins. This is an expected outcome, since tidal acceleration caused by interaction with a stellar companion is only important for orbital periods of only a few days, depending on how massive the companion is (see, e.g., Ferraz-Mello et al. 2015).

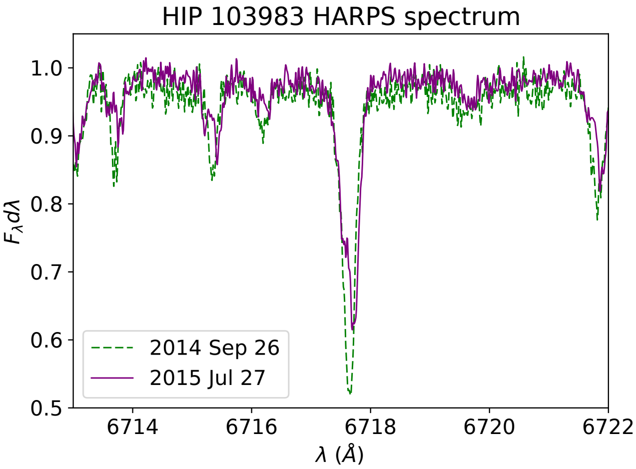

Figure 5. Same as Fig. 4, but for HARPS spectra of the double-lined solar twin binary HIP 103983.

Among the 18 spectroscopic binaries we studied, four of them have new companions that were not previously reported in the literature. These are: HIP 6407, HIP 30037, HIP 54582 and HIP 62039. For the first one, its companion is likely an eccentric red dwarf with minimum mass 0.12 $M_\odot$. The last three binaries likely have very low-mass companions that are either brown dwarfs or giant planets. The last two have very large orbital periods (> 100 yr) that are not easily constrained with the radial velocities data available. Such long period binaries are viable targets for further characterization using direct imaging methods.

5. Conclusions

By employing high-quality HARPS spectra and radial velocities of bright stars strictly similar to the Sun, we have performed the largest study on the rotational evolution of solar twins using spectroscopic data. We concluded that the Sun is indeed a regular rotator for its age when compared to solar twins, and that it is thus viable to use it to calibrate empirical relations such as gyrochronology.

We also found that the solar twins seem to follow an evolutionary path that differs from the widely used Skumanich law: their rotational velocities decay faster during the first 1 Gyr, but even more striking is the observation that these velocities stagnate into a plateau after the solar age. This has strong implications for gyrochronology, since the ages inferred from $v \sin i$ may have large uncertainties for Sun-like stars. On the other hand, based on theoretical models of stellar evolution, we expect that the rotational periods of Sun-like stars continue evolving after the solar age, especially by the end of the main sequence; thus our results do not rule out gyrochronology based on rotational periods.

Among the 18 spectroscopic binaries in our sample, we found that three of them, HIP 19911, HIP 67620 and HIP 103983, display a significantly high rotational velocity for their respective ages. After a careful analysis of the radial velocities and spectra, we concluded that these and other anomalies, such as high chromospheric activity and large RV residuals, are likely due to contamination by their bright nearby companion – i.e., these are double-lined spectroscopic binaries. This means that the other binaries in the sample, which have low-mass companions ($m \sin i < 0.6$ $M_\odot$) at moderate to large orbital (> 30 days) periods are likely to follow the same evolutionary path of rotation that single stars do.

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